TESTS AND ANALYSIS FOR SAFE DISTANCES
FROM
HIGH PERFORMANCE MAGAZINE OVERPRESSURE AND DEBRIS

by

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ABSTRACT

The High Performance (HP) Magazine is an ordnance storage concept that will reduce the land encumbered by ESQD (Explosives Safety Quantity Distance) arcs and improve the efficiency of weapons handling operations. The HP Magazine uses a reinforced concrete roof with soil cover to mitigate the fragment and debris hazard. The mass from thicker than normal soil cover (> 2 feet) controls fragment and debris distances. Tunnel exits are used to restrict shock propagation and control safe pressure distance and reduce the total encumbered land area.

Twelve small-scale (1/10) and one large-scale (1/4) tests were conducted by the Energetic Materials Research & Testing Center (EMRTC) at Socorro, NM in 1991 - 1994. For the 1/10-scale tests, a reusable magazine test fixture was built and twelve tests were performed in which 2.4-inch thick reinforced roof slab specimens were covered with 0, 3.6, 5.4, or 12.0 inches of soil. The explosive test charges were rectangular blocks of Composition C4 (equivalent to 10, 15, or 55 pounds of TNT). The 1/4-scale test structure had 24 inches of soil above a 10.5-inch thick reinforced concrete roof. The explosive charge was five rectangular blocks of Composition C4 (equivalent to a total of 859.4 pounds of TNT). Data included airblast instrumentation, high-speed motion pictures, and debris recovery.

The measured interior and exterior blast pressures will be presented and compared with values from current prediction methods. The recovered debris will be used to determine safe debris distances and compare to values predicted with the analytical model DISPRE.

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INTRODUCTION

Background

The High Performance (HP) Magazine (Reference 1) is an ordnance storage concept, under development by NFESC, that will reduce the land encumbered by ESQD (Explosives Safety Quantity Distance) arcs and improve the efficiency of weapons handling operations. This magazine can reduce encumbered land by 80% and significantly reduce operational costs. The magazine is being designed to store 250,000 pounds Net Explosive Weight (NEW) of palletized ordnance (e.g., bombs, bullets, projectiles, torpedoes) or 125,000 pounds NEW of containerized missiles. The most important factor in the improved performance of the magazine is the reduction of the Maximum Credible Event (MCE) to about 30,000 pounds NEW of High Explosive (HE) in any storage cell and less than about 50,000 to 80,000 pounds NEW in the Shipping and Receiving Area (SRA). These MCEs are limited by using interior walls and magazine architecture that prevent sympathetic detonation (SD) between cells and the SRA.

The safe ESQDs are given in Reference 2. For standard earth-covered magazines, the overpressure ESQD arc for an MCE of 30,000 pounds is 1,088 feet to the front and side ($35W^{1/3}$) and 777 feet to the rear ($25W^{1/3}$), the range at which the peak pressure decays to 1.2 psi. This is much less than the ESQD arc for debris and fragments which is 1,250 feet (the range for a hazardous debris density of 1/600 ft^2). The debris and fragment safe distance for the HP Magazine must be reduced in order to take full advantage of the reduced MCE.

The HP Magazine uses a reinforced concrete roof with soil cover to mitigate the fragment and debris hazard. The roof and soil cover must stop high velocity primary weapon fragments and control the roof and soil cover safe debris distance. The mass from thicker than normal soil cover (> 2 feet) controls fragment and debris distances. Tunnel exits are used to restrict shock propagation and control safe pressure distance and reduce the total encumbered land area.

NFESC has completed Phase I of the feasibility testing of a 1/10-scale model HP Magazine that investigated the effects of soil cover depth and roof support conditions on the safe pressure and debris distance outside the magazine (References 3 & 4). The tests (Test Nos. 1-6) showed that soil cover and tunnel exits do reduce the debris and pressure safe distances at least as well as expected. However, not all of the key parameters (such as charge density and tunnel diameter) could be tested in the limited feasibility test program. Locating the SRA inside the magazine was a recent design change. It is necessary to determine the effects of the SRA on safe distances since it is much larger, and contains a much larger MCE (NEW = 55,000 pounds TNT), than the storage cell tested in Phase I. The effect of water in the near proximity of the MCE on internal quasi-static pressures and resulting safe debris and pressure distance must also be determined.

Objectives

Accurate methods do not exist for determining the HP Magazine internal and external loads, roof/soil cover breakup, and safe debris distance. Testing is necessary to improve and verify existing methods and to develop new analytical methods. Small-scale tests are required to inexpensively determine the effect of the many variables that effect the performance of the HP Magazine roof. The small-scale parameter tests will be used to verify the applicability of the existing analytical methods, and to provide data to improve the methods for the specific geometry of the HP Magazine. The small-scale tests are also necessary to show the feasibility of the concept for limiting safe hazard distances to about 1,000 feet.

The objective of this Phase II test program is to determine the effect of roof & soil cover design parameters on safe debris and pressure distances. The six Phase I tests did not adequately cover the range of magazine design parameters needed for prototype design. The six Phase II tests will complete the small-scale tests and shall include a study of one versus two tunnel exits, explosive charge weights in both the storage cell and SRA, and water walls.

Scope

Scale model testing (scale factor, F_s = 1/10) will be used to determine the effect of the key variables on safe debris range (scaled distance at which the debris density = 1 hazardous fragment per 600 ft^2) and safe pressure range (scaled distance at which the peak incident pressure = 1.2 psi). Geometric scaling (model dimensions = F_s * full-scale dimensions) will be used to properly scale most key parameters (gravity being the important exception). Geometric scaling (especially at the relatively large scale of 1/10) has been shown to be accurate for modeling the pressure environment. NEW scales as F_s^3.

The key variables to be investigated are charge density (W/V), roof & soil weight, number and location of exits, presence of water, and location of donor explosives. The scope of the test program is outlined in Table 1. The following list show some of the specific test parameters which were investigated:

- **Explosive Donor:** Single charge
Multiple charges
- **Explosive Charge Weight:** NEW = 10, 15, & 55 pounds TNT
- **Soil Cover:** 5.4 inches
12.0 inches
- **Tunnel Exit Configuration:** One exit at each end
One exit at SRA end
- **Donor Cell Walls:** Sand-filled CMU block
Water-filled plexiglass wall

TEST SETUP

Test Site

The six tests were conducted in the West Valley area of the Energetic Materials Research & Testing Center (EMRTC) Field Laboratory located at the New Mexico Institute of Mining and Technology (NMIMT) in Socorro, New Mexico. The site dimensions, shown in Figure 1, are the same as used for the Phase I tests. The outside boundaries were determined from the debris recovery and pressure gauge line requirements. Debris recovery areas and pressure gauge lines are also shown in Figure 1. The area was re-bladed and re-rolled prior to the test program and cleared of most debris between each test.

Test Fixture

A reusable magazine test fixture (with replaceable center walls and donor cell walls) was provided to conduct the 1/10-scale tests of HP Magazine roof specimens (see Figure 2). The fixture consists of 4-feet thick by 4-feet high (outside dimension) reinforced concrete walls poured monolithically with a 2-1/2 feet-thick reinforced concrete floor. The inside of the walls were lined with 3/8-inch thick steel plate. The fixture was designed as a partial containment cubical with venting through the open tunnel exits and the frangible roof and soil cover. The blast loads acting on the inside faces of the walls were resisted by transferring the loads into the floor which was heavily reinforced with two horizontal layers of #6 "tension" bars spaced @ 10 inches in each direction. Each end of these continuous "tension" bars was bent 90^{o} upward into the wall. To help transfer the load downward into the floor, #6 vertical bars spaced at 10 inches were located near the inside face of the four walls and crossed through the potential horizontal shear crack. The test fixture was also strengthened by placing three #6 flexural bars in each face of the four walls. These flexural rebars were tied together with #4 closed-ties spaced at 18 inches. No diagonal rebars were used at any of the sidewall/endwall, sidewall/floor, or endwall/floor corners. The top of the fixture was flat to simply support a 3-inch wide roof slab bearing surface. 1-inch diameter embedded hook bolts were spaced at 12 inches to provide translational/rotational edge restraint in all six roof slabs. Each end wall has two 16-inch diameter circular exits that can be closed off with 3/4-inch thick steel plates to obtain the proper test exit configuration (D10 or D11 per Table 1). In Test 7, the roof specimen was supported along the magazine center by a continuous 2x4 wood beam resting on 4x4 (column) wood supports to the floor. The column/beam fixture was enclosed with plywood sheeting and then filled with sand. In Tests 8-12, this full-height center wall was constructed of 8-inch standard concrete masonry units (CMU) filled with sand. The wall was stopped 37.9 inches from the open-tunnel end of the test fixture. In Test 7, the donor cell was simulated with 3-inch thick unreinforced concrete walls with the dimensions shown in Table 1. In Tests 8, 10, and 11, the donor cell was simulated with sand-filled 6-inch CMU blocks with the dimensions shown in Table 1. In Test 9, these CMU donor cell walls were replaced with 1.4-inch thick water walls (i.e., water enclosed within an open-top, plexiglass wall system). In Test 12, a 15.1-inch high by 47.9-inch long donor cell wall (constructed of sand-filled 8-inch CMU blocks) was placed perpendicular to the center wall at the 37.9-inch location. Photographs of the completed test fixture for Tests 8 and 12 are shown in Figure 3.

Roof Specimens

The reinforced concrete roof slabs are identical to those built for the Phase I tests (Figure 4). The test plan called for a concrete mix proportioned for a 28-day compressive strength of 4,000 psi. Figure 5 shows the distribution of the fine and coarse aggregate used in the following mix:

0.60/1.0/1.30/2.28

These numbers denote relative weights of water, cement, fine and coarse aggregate. Each slab was tinted with a different colored admixture to facilitate debris analysis. The strength results of concrete test cylinders cast during the pouring of the six roof slabs are listed in Table 2.

The reinforcing steel in the 6-1/2 feet x 6-1/2 feet area directly above the donor explosive (as shown in Figure 4) modeled the flexural and shear steel in a full-scale static design for a roof with 4 feet of soil cover. In Test 12, the donor was located in the SRA end of the magazine. Therefore, the slab for Test 12 was constructed with the 6-1/2 feet long x-section "A" located adjacent to the short edge of the specimen. To reduce cost, the concrete x-section "B" away from the donor charge did not include the shear stirrups. These areas of the slab were not expected to breach and therefore the shear steel requirements were relaxed. The flexural strength in these areas was unchanged. In the full-scale design, the required main flexural steel is as follows:

Grade 60, #9 rebar		
Static design yield stress, f_s	66,00	psi
Bar diameter, d	1.128	inch
Bar area, A	1.0	$inch^2$
Bar spacing, s	10	inches
Distance between centroids of compression & tension rebar, d_c	19.1	inches

Ideally, the model reinforcement should be made of the same material with the following 1/10-scale properties:

Bar diameter, d	0.113	inch
Bar area, A	0.010	$inch^2$
Bar spacing, s	1.0	inch
Distance between centroids of compression & tension rebar, d_c	1.91	inches

In designing the model structure, compromises were made in rebar strength, size and spacing to reduce costs and simplify construction, while keeping the moment capacity (i.e., A f_s d/s) approximately unchanged. The final model main reinforcement selected was a carbon steel, welded wire cloth with the following properties:

Static yield stress, f_s	86,636	psi
Bar diameter, d	0.120	inch
Bar area, A	0.0113	$inch^2$
Bar spacing, s	1.12	inches
Distance between centroids of compression & tension rebar, d_c	1.85	inches

The model shear reinforcing was double leg stirrups made from 20 gauge 60 ksi wire (which corresponded to single leg #4 stirrups at full-scale).

Soil Cover

The soil cover used in all tests was uncompacted dry sand. A uniform density of 100.0 pcf was consistently achieved by simply dropping the sand from a skip loader onto the roof slabs. A photograph of the Test 12 roof slab with soil cover just prior to testing is shown in Figure 6.

Explosive Donor

Rectangular Composition C4 explosive charges were constructed to simulate (1/10-scale) the full-scale magazine MCEs of 10,000 pounds, 15,000 pounds, and 55,000 pounds NEW of TNT. The NEW for these tests were 10 pounds, 15 pounds, and 55 pounds TNT equivalent, based on gas pressure equivalency. The actual weight of Composition C4 required to produce the same peak gas pressures as TNT was determined from Reference 5 and is shown below for the six tests:

Test No.	**TNT Equivalency**	**Composition C4 W (pound)**	**Height (inch)**	**Width (inch)**	**Length[1] (inch)**
7	1.36	7.37	4	5	6.2
8,9	1.39	7.17	4	5	6.2
10	1.39	7.17[2]	4	5	6.2
11	1.37	10.92	4	5	6.2
12[3]	1.33	41.22	6.6	5.1	6.2

[1]The length was varied in order to obtain the exact charge weight
[2]The total charge weight of 7.17 pounds consists of three separate 2.39-pound charges

[3]Dimensions are proportional to a prototype boxcar (10-feet wide, 13-feet high, 41-feet long)

The bottom of the explosive charges was located 2.2 inches off the steel floor plate.

Data Requirements

Airblast. The airblast instrumentation consisted of 28 gauge stations (only 24 stations were active for each test): 23 stations external to the test fixture and 5 stations internal to the test fixture. Piezo-resistive pressure transducers were used at all stations except the two piezo-electric PCB transducers used at Stations SP-1 and SP-2 (Test 7 only). The signals from the transducers were recorded on magnetic tape by Honeywell Model 101 14-track FM tape recorders operating at 120 ips. The system bandwidth was 80-kHz. A programmable sequence-control timer detonated the charge and operated the recording system. The data for each test were later digitized, processed, and plotted.

The external pressure gauges were surface mounted to measure incident blast overpressures along gauge lines to the front ('F'), on a diagonal ('D'), to the side opposite the center of the test fixture ('S'), and to the back ('B'). External pressure gauge locations are shown in Figure 7.

The internal pressure gauges were located inside the test fixture to measure the shock and gas overpressures. Two of the gauges measured the internal shock overpressures just inside the front and back tunnel exits at the cylinder bottoms. The other three gauges measured the gas pressure inside the fixture and were located in opposite long walls of the test fixture and, in Tests 8-12, on the steel plate blocking the back tunnel exit. The gauge was thread-mounted at mid-height of the test fixture so the gauge diaphragm was flush with the face of the wall or plate. A perforated steel filter was placed over the diaphragm to protect it from internal debris and attenuate the shock pressures. The internal pressure gauge locations are also shown in Figure 7.

Photographic Coverage. Four high-speed motion picture cameras and one real-time video camera were used in each test. The high-speed cameras (Nos. 1 through 4) were used to measure initial debris angle and velocity. The real-time camera (No. 5) was used to cover the overall event. Camera locations are shown in Figure 8.

Debris Recovery. Debris was recovered and characterized by EMRTC. The debris recovery zones were two 5-degree sectors to the front and side of the test fixture, as shown in Figure 9. The recovery sector to the side began at 40 feet from the inside wall of the test fixture and extended to 460 feet. The recovery sector to the front began at 41-3/4 feet from the inside wall of the test fixture and extended to 241-3/4 feet. A concrete pad was used in the first 200 feet of each 5-degree sector. The debris recovery zones were formed by the 5-degree boundaries and radii at 20-feet spacings. All debris was collected in the recovery zones. Debris passing through a 3.35 mm sieve was not analyzed. A sieve analysis (using 4.75mm and 6.35 mm sieves) was run on debris retained by the 3.35 mm sieve but passed by a 9.50

mm sieve. The debris retained by the 3.35 mm sieve was counted and collectively weighed. The debris retained by the 4.75 mm and 6.35 mm sieves was counted and individually weighed. The debris retained by the 9.5 mm sieve was individually weighed, and measured (length, width, and thickness). Individual debris outside the recovery zones was mapped by EMRTC. About 100 pieces of the largest debris and at the greatest distances were recovered for each test. This debris was categorized by size as described above for the debris retained by a 9.50 mm sieve.

TEST RESULTS

Reference 6 contains the digitized data, recorded at the test site altitude of 5,420 feet above sea level, for the internal and external pressure gauges of all six tests. Impulses were obtained by numerically integrating the digitized pressure data. No filtering of the data was employed. The data for each test are referenced to a common zero time (Time of Detonation) and are displayed with time in milliseconds as the abscissa. Typical data records are shown in Figure 10. The values of the measured peak pressures in all six tests are listed in Table 3. However, in order to compare the external pressure data with the results from analytical prediction models, the data must be converted to sea level conditions. To convert to sea level, the following computational procedure (Reference 7) was followed:

1. Calculate the correction factors for distance (S_d) and pressure (S_p):

$$S_d = (p_{ao}/p_{az})^{1/3}$$
$$S_p = p_{az}/p_{ao}$$

where,

p_{ao} = atmospheric pressure at sea level, 14.7 psi
p_{az} = atmospheric pressure at altitude z, psi
$p_{az} = 14.7[288.15/(288.15 - 0.0019812\, z)]^{-5.25588}$, psi
z = altitude above sea level, feet

For z = 5,420 feet (Test site altitude):

p_{az} = 12.04 psi
S_d = 1.069
S_p = 0.819

2. Convert the gauge distances to sea level values:

$$R_o = R_z/S_d = 0.936\, R_z$$

e.g., Gauge F-1: R_z = 20.00 feet

$R_o = 18.72$ feet

3. Convert the actual measured peak pressures to sea level values:

$$p_o = p_z/S_p = 1.221\ p_z$$

e.g., Gauge F-1 in Test No. 8: $p_z = 4.33$ psi

$$p_o = 5.29 \text{ psi}$$

The adjusted peak pressures and ranges for the six tests are listed in Table 4. Reference 6 also contains the complete records of the debris collected from all six tests. High speed films showing test results are in the possession of NFESC. However, this paper will be limited to the results/discussion of Tests 8, 11, and 12. Tests 8 and 11 are identical (i.e., one tunnel exit and soil cover = 5.4 inches) except for the charge weight (W = 10 pounds TNT for Test 8; W = 15 pounds TNT for Test 11). In Test 12, the charge weight and soil cover were increased to 55 pounds TNT and 12.0 inches, respectively, and the charge location was moved to the SRA end of the magazine.

Observed Structural Response/Breakup

Review of the videos/high-speed films combined with visual studies of the condition of the tested roof slabs produced the following general observations:

- The roof slabs were lifted off the test fixture as a rigid body and propelled straight upward. The maximum vertical lift occurred in Test 12 and the minimum occurred in Test 8.

- The final resting positions of the roof slabs were within or very close to the boundaries of the test fixture.

- Breaching of the roof slabs occurred directly above the location of the explosive charge. The amount of breaching was directly proportional to the charge weight.

Post-test photographs of the three tested slabs are contained in Figures 11 through 14.

Pressure Data Analyses

The pressure outside the test fixture consists of two components: (1) directional leakage pressure from the tunnel exits and (2) leakage pressure through the breached roof and soil cover. A detailed explanation of the methods developed to calculate the pressures from these two physical phenomena are contained in Reference 6.

The method used to calculate the external pressure from the tunnel exits was developed by the

U.S. Army Ballistics Research Laboratory (Reference 8). The following relationship is applicable for magazines with one tunnel exit:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_o/(1.173\ D)]^{-1.35} \tag{1}$$

where,

p_o = peak pressure at distance R_o, psi
R_o = distance from opening along centerline axis (0^o line), feet
W = explosive storage weight, pounds
V = total volume of chamber (test fixture) and tunnels, $feet^3$

for $W/V \leq 0.025$,	$d = 4000$ $b = 0.82$
for $0.025 < W/V < 0.07$,	$d = 945$ $b = 0.43$
for $W/V \geq 0.07$,	$d = 2675$ $b = 0.82$

A_t = cross-sectional area of the tunnel opening, $feet^2$
A_c = cross-sectional area of the chamber (test fixture), $feet^2$
D = equivalent circular cross-sectional diameter of tunnel, feet

This equation is partially based on the following two equations for peak gas pressure inside the chamber (p_c) and peak pressure at tunnel exit (p_x):

$$p_c = d(W/V)^b \tag{2}$$
$$p_x = 1.733(P_c)^{0.83}(A_t/A_c)^{0.19} \tag{3}$$

The equation for p_o along any line "a" degrees from the 0^o line is given as:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_a/(1.173\ D\ F_a)]^{-1.35} \tag{4}$$

where,

R_a = distance from opening along "a" line, feet
F_a = $[1 + (a/56)^2]^{-0.741}$

Exit pressures for multiple tunnels (2) were calculated, at a given range and azimuth, by conservatively adding the peak pressures calculated from Equation 4 for each tunnel exit.

The method used to calculate the external pressure from the leakage through the breached roof and soil cover is based on procedures (Reference 9) developed by the U.S. Army

Waterways Experiment Station (WES). The following relationship is for fully-coupled buried charges (explosive charge in direct contact with soil cover):

$$p_o = 3.51\,(h/W^{1/3})^{-2.7}\,(R/W^{1/3})^{-1.06} \qquad (5)$$

where,

p_o = peak pressure at distance R, psi
h = cover depth, feet
R = horizontal distance from explosive source, feet
W = explosive weight, pounds

However, our tests were considered as decoupled buried charges (air gap between charge and soil cover). WES has determined the following coupling factor (C_{cf}) to relate fully-coupled and decoupled buried charges:

$$C_{cf} = 0.03358\,(W/V)^{0.4555}$$

where,

W = decoupled explosive weight, kilograms
V = total chamber volume, meter^3

The equivalent fully-coupled charge weight is:

$$W_{cf} = C_{cf}\,W$$

Calculation of W_{cf} allows the use of the relationship (Equation 5) developed for fully-coupled charge weights.

The predicted peak gas and tunnel exit pressures were calculated from Equations 2 and 3 and listed below:

	Peak Pressure (psi) for Test No.		
Pressure Measurement	**8**	**11**	**12**
Gas Pressure, P_c	305	425	1,253
Exit Pressure, P_x	140	185	453

The tunnel exit pressure data (SP gauges) was very poor and not usable. The gas pressure data (GP gauges) was only slightly better. Figure 10 shows a typical pressure-time history for each of the three tests. In spite of the perforated steel plate filter covering the GP gauge diaphragm, the severe environment inside the test fixture made it difficult to compare the test data listed in Table 4 with the above predictions.

The predicted peak external pressures from the two methods were calculated in Reference 6 for all six tests. Although the peak pressures from these two components will occur at different times, they were added to obtain the conservative test predictions listed in Table 5. As an example, the predicted pressures for Test 8 are plotted versus range in Figure 15 for the four directions (i.e., front, diagonal, side, and back). The measured external peak pressures for Test 8 listed in Table 4 are also plotted in Figure 15. The test data for each test are very similar. Relatively good agreement of the measured and predicted peak pressures occurred for Tests 8, 11 and 12.

Debris Data Analyses

Debris Outside Recovery Sectors. Locations of the debris collected in Tests 8, 11, and 12 are shown in Figures 16, 17, and 18. Also shown on each figure are the following two debris distances predicted by the "Building Debris Hazard Prediction Model, DISPRE" (Reference 10):

- Small-scale maximum debris distance

- Full-scale minimum safe debris distance (includes 1.3 safety factor required by DDESB)

Analyses of the debris collected outside the recovery sectors in Tests 8 and 11 indicate that the maximum debris distance was increased by increasing the charge weight from 10 to 15 pounds TNT. In Test 12, the charge weight was further increased to 55 pounds TNT but the soil cover was also increased from 5.4 inches to 12.0 inches. Both the measured and predicted maximum debris distance in this test were greater than Tests 8 and 11.

Debris Within Recovery Sectors. An example of the debris areal distribution by zone is shown in Table 6 for the side recovery sector of Test 11. This table contains all debris with mass greater or equal to the 1/10-scale critical mass[1] of 0.000375 lb (2.6 grains). This 1/10-scale debris data was scaled up by applying the trajectory relationship between a 1/10-scale debris and full-scale debris. This relationship is graphically shown in Figure 19 and is valid for a 1/10-scale mass of 0.038 lb (average mass of debris collected in the large debris mapping area) at an initial angle of 40° above the horizontal. The full-scale debris areal number density, calculated as the cumulative number of debris per 600 ft^2, is listed in this table and shown in Figure 20. The debris densities for all six tests to the side and front directions are shown in Figures 20 and 21, respectively. The debris hazard range is defined to be that range beyond which the areal number density of hazardous fragment is one per 600 ft^2 or below. The hazardous range for the three tests were graphically obtained from the above

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[1]Trajectory (Reference 11) calculations found that critical debris with a mass of 0.000375 pound or larger are hazardous (58-ft/lb) upon impact.

figures and are listed in Table 7. Also listed in this table are the safe debris ranges predicted by DISPRE.

CONCLUSIONS

The external pressures predicted by the methods outlined in this paper compared very well with the measured pressures to the front, diagonal, side, and back directions for Tests 8, 11, and 12. Because the test fixture had only one tunnel exit, the pressures to the front were the greatest, while the pressures to the side and back were considerably less. In this controlling front direction, the measured pressures were less than predicted. At the 1.2 psi range, the measured pressures were about 25, 32, and 39 percent less than predicted for Tests 8, 11, and 12, respectively. Thus, the determination of safe pressure distance to the front using the prediction methods would be conservative. However, in the side and back directions, the measured pressures were greater than predicted, and therefore the determination of safe pressure distance using the prediction methods would be unconservative in these directions.

The 1/10-scale measured safe pressure distances (i.e., distance from the test fixture exterior that the peak pressure decays to 1.2 psi) to the front, diagonal, and side directions for Tests 8, 11, and 12 are listed in Table 8. In the controlling front direction, the scaled measured
safe pressure distances ranged from 21.1 to 24.0 feet/pound$^{1/3}$, less than the 35W$^{1/3}$ ESQD arc required by OP 5 for earth-covered magazines. The safe pressure distance for a full-scale HP magazine with an MCE of 55,000 pounds would equal 916 feet, less than the 1,000-foot test program objective.

The worse-case measured full-scale safe debris distances listed in Table 7 were multiplied by the DDESB required 1.3 safety factor. These adjusted measured values were 20, 35, and 46 percent less than predicted for Tests 8, 11, and 12, respectively, and except for Test 12 (R_{safe} = 1,040 feet) were all less than the desired 1,000-foot test program objective.

It is concluded that the HP Magazine concept can mitigate the fragment and debris hazard and that the required safe pressure and debris hazard ranges will significantly reduce the total area encumbered by ESQD arcs.

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8. U.S. Army Ballistics Research Laboratory. Briefing to DDESB Secretariat: Proposed Quantity - Distance Criterion for Accidental Explosions in Underground Storage Sites, by Charles Kingery, George Coulter, and Gerald Bulmash. Aberdeen, MD, February 1988.

9. U.S. Army Waterways Experiment Station. Paper presented to DDESB Tri-Service Committee on Underground Storage: Cover Vented Overpressure, by Charles E. Joachim. Vicksburg, MS, May 1990.

10. Southwest Research Institute. Technical Report: Building Debris Hazard Prediction Model, by Patricia M. Bowles, Charles J. Oswald and Luis M. Vargas. San Antonio, TX, February 1991.

11. Naval Surface Warfare Center. Technical Paper: TRAJ -- A Two Dimensional Trajectory Program For Personal Computers, by Paul E. Montanaro. Published in Seminar Proceedings, 24th DDESB Seminar, St. Louis, MO, August 1990.

Table 1
Schedule of Phase II Tests

Test No.	Charge Weight, W (lb)		Roof/Soil Cover Configuration	Roof[1] Weight (pcf)	Tunnel[2] Exit and Location	Donor Cell Size L x D x H (in.)	Total Volume[3], V_t (ft^3)
	Comp C-4	TNT					
7	7.37	10	2.4" roof +5.4" soil	78.5	2 exits (D11)	19x19x9.5	152.5
8	7.17	10	2.4" roof +5.4" soil	78.5	1 exit (D10)	19x19x9.5	141.4
9	7.17	10	2.4" roof +5.4" soil	78.5	1 exit (D10)	19x19x9.5	141.4
10	7.17[4]	10	2.4" roof +5.4" soil	78.5	1 exit (D10)	65x19x9.5	141.4
11	10.92	15	2.4" roof +5.4" soil	78.5	1 exit (D10)	19x19x9.5	141.4
12	41.22	55	2.4" roof +12.0" soil	139.0	1 exit (D10)	72x37.9x15.1	138.7

[1]Roof slab density = 145 pcf
Soil density = 110 pcf
[2]Exit configuration key: D10 = 1 exit at one end; D11 = 1 exit at each end
[3]$V_t = V_{test\ fixture} + V_{tunnel(s)} - V_{interior\ walls}$
[4]The total charge of 7.17 pounds consists of three separate 2.39-pound charges

Table 1 Schedule of Phase II Tests

Table 2
Compressive Test Results for Concrete Test Specimens
Cast During Roof Slab Construction

Test No.	Roof Color	Date Poured	Date Tested	Days Cured	Compressive Strength, f_c' (psi)
7	Orange	7/17/92	8/28/92	42	4,192
8	Red	7/24/92	9/01/92	39	4,644
9	Black	8/02/92	9/03/92	32	5,271
10	Neutral	8/04/92	9/17/92	44	4,181
11	Yellow/Brown	8/13/92	9/22/92	40	3,725
12	Lt. Green	8/15/92	9/24/92	40	4,665

Table 2 Compressive Test Results for Concrete Test Specimens Cast During Roof Slab Construction

Table 3
Measured Peak Pressures at Altitude

Gauge No.	Range R_z (ft)	Peak Pressure for Test No., p_z (psi)					
		7	8	9	10	11	12
SP-1	---	551.0	---	293.4	308.5	358.7	---
SP-2	---	507.4	---	---	---	---	---
GP-1	---	144.5	213.0	183.5	240.9	325.6	2202.5
GP-2	---	281.7	396.8	217.2	376.6	477.4	849.7
GP-3	---	---	488.0	914.5	615.2	850.5	829.8
F-1	20	5.33	4.33	4.23	5.06	6.62	---
F-2	30	2.73	2.27	2.06	2.38	3.16	6.85
F-3	40	1.63	1.39	1.25	1.41	1.80	3.51
F-4	55	0.89	0.79	0.68	0.86	0.96	2.07
F-5	75	0.57	0.52	0.45	0.58	0.65	1.50
F-6	100	0.42	0.36	0.32	0.39	0.43	0.95
F-7	150	0.23	0.17	0.13	---	0.26	0.49
F-8	200	---	---	---	---	---	0.34
D-1	20	---	---	3.94	4.62	6.38	---
D-2	40	1.66	1.39	1.21	1.50	1.94	4.11
D-3	55	---	0.73	0.70	0.91	1.16	2.06
D-4	75	0.70	0.56	0.54	0.64	0.75	1.49
D-5	100	0.46	0.39	0.39	0.49	0.53	0.99
D-6	150	---	---	---	---	---	0.66
S-1	15	1.93	1.07	1.04	0.98	1.60	---
S-2	20	1.92	0.90	0.87	0.85	1.36	2.46
S-3	30	1.50	0.80	0.72	0.58	0.91	2.11
S-4	50	1.26	0.46	0.41	0.49	0.68	1.33
S-5	75	0.86	0.31	0.27	0.26	0.35	0.73
S-6	100	---	---	---	---	---	0.69
B-1	20	6.68	0.22	0.150	0.18	0.29	0.86
B-2	55	1.19	0.12	0.082	0.14	0.17	0.44
B-3	100	0.55	0.08	0.075	---	0.11	0.27

Table 3 Measured Peak Pressures at Altitude

Table 4
Measured Peak Pressures Adjusted for Sea Level

Gauge No.	Adjusted Range R_o (ft)	Adjusted Peak Pressure for Test No., p_o (psi)					
		7	8	9	10	11	12
SP-1	---	551.0	---	293.4	308.5	358.7	---
SP-2	---	507.4	---	---	---	---	---
GP-1	---	144.5	213.0	183.5	240.9	325.6	2202.5
GP-2	---	281.7	396.8	217.2	376.6	477.4	849.7
GP-3	---	---	488.0	914.5	615.2	850.5	829.8
F-1	18.72	6.51	5.29	5.16	6.18	8.08	---
F-2	28.08	3.33	2.77	2.52	2.91	3.86	8.36
F-3	37.44	1.99	1.70	1.53	1.72	2.20	4.29
F-4	51.48	1.09	0.96	0.83	1.05	1.17	2.53
F-5	70.20	0.70	0.63	0.55	0.71	0.79	1.83
F-6	93.60	0.51	0.44	0.39	0.48	0.53	1.16
F-7	140.40	0.28	0.21	0.16	---	0.32	0.60
F-8	187.20	---	---	---	---	---	0.42
D-1	18.72	---	---	4.81	5.64	7.79	---
D-2	37.44	2.03	1.70	1.48	1.83	2.37	5.02
D-3	51.48	---	0.89	0.85	1.11	1.42	2.52
D-4	70.20	0.85	0.68	0.66	0.78	0.92	1.82
D-5	93.60	0.56	0.48	0.48	0.60	0.65	1.21
D-6	140.40	---	---	---	---	---	0.81
S-1	14.04	2.36	1.31	1.27	1.20	1.95	---
S-2	18.72	2.34	1.10	1.06	1.04	1.66	3.00
S-3	28.08	1.83	0.98	0.88	0.71	1.11	2.58
S-4	46.80	1.54	0.56	0.50	0.60	0.83	1.62
S-5	70.20	1.05	0.38	0.33	0.32	0.43	0.89
S-6	93.60	---	---	---	---	---	0.84
B-1	18.72	8.16	0.27	0.183	0.22	0.35	1.05
B-2	51.48	1.45	0.15	0.100	0.17	0.21	0.54
B-3	93.60	0.67	0.10	0.092	---	0.13	0.33

Table 4 Measured Peak Pressures Adjusted for Sea Level

Table 5
Predicted Peak External Pressures at Sea Level

Gauge No.	Location		Peak Pressure for Test No., p_o (psi)				
	Azimuth (degree)	Adjusted Range R_o (ft)	7	8 and 10	9[1]	11	12
F-1	Front (0)	18.72	4.98	5.00	1.30	6.66	16.31
F-2		28.08	2.91	2.90	0.75	3.87	9.48
F-3		37.44	2.00	1.98	0.51	2.64	6.46
F-4		51.48	1.31	1.28	0.34	1.72	4.22
F-5		70.20	0.87	0.86	0.23	1.14	2.79
F-6		93.60	0.60	0.58	0.15	0.78	1.90
F-7		140.40	0.35	0.33	0.08	0.46	1.11
F-8		187.20	0.24	0.23	0.06	0.31	0.76
D-1	Diagonal (30)	18.72	3.94	3.91	1.01	5.22	12.79
D-2		37.44	1.60	1.55	0.40	2.07	5.07
D-3		51.48	1.05	1.01	0.26	1.35	3.32
D-4		70.20	0.71	0.67	0.18	0.89	2.19
D-5		93.60	0.49	0.45	0.11	0.61	1.50
D-6		140.40	0.28	0.26	0.07	0.36	0.87
S-1	Side (90)	14.04	1.63	0.92	0.23	1.34	3.23
S-2		18.72	1.39	0.77	0.19	1.11	2.69
S-3		28.08	1.03	0.56	0.14	0.80	1.95
S-4		46.80	0.63	0.34	0.09	0.49	1.18
S-5		70.20	0.40	0.220	0.055	0.32	0.76
S-6		93.60	0.29	0.157	0.040	0.22	0.54
B-1	Back (180)	18.72	4.98	0.229	0.054	0.371	0.885
B-2		51.48	1.31	0.100	0.024	0.158	0.379
B-3		93.60	0.60	0.055	0.013	0.088	0.209

[1]Assume water wall reduces peak pressures outside the test fixture by 74 percent through the tunnel exit and 80 percent through the soil cover.

Table 5 Predicted Peak External Pressures at Sea Level

Table 6
Debris Density in Side Recovery Sector for Test 11

Zone Nomenclature	1/10 - Scale			Full-Scale		
	Range,[1] R_z (ft)	Number Debris N	Cumulative Number Debris N_t	Range,[2] R_z (ft)	Area,[3] A_z (ft^2)	Debris Density (No./600 ft^2)
S21	460	0	0	2829.0	52,811	0.00
S20	440	0	0	2609.0	49,344	0.00
S19	420	0	0	2385.0	44,710	0.00
S18	400	0	0	2163.2	37,130	0.00
S17	380	0	0	1959.9	35,015	0.00
S16	360	0	0	1747.0	28,501	0.00
S15	340	0	0	1552.7	24,159	0.00
S14	320	0	0	1367.0	19,819	0.00
S13	300	0	0	1193.8	15,990	0.00
S12	280	0	0	1033.7	12,622	0.00
S11	260	0	0	887.8	10,119	0.00
S10	240	5	5	751.4	8,127	0.37
S9	220	1	6	632.3	6,558	0.55
S8	200	2	8	518.9	3,863	1.24
S7	180	4	12	438.3	3,300	2.18
S6	160	14	26	357.6	2,670	5.84
S5	140	27	53	278.7	1,270	25.04
S4	120	31	84	231.6	1,076	46.84
S3	100	39	123	184.5	882	83.67
S2	80	70	193	137.4	688	168.31
S1	60	82	275	90.3	313	527.16

[1]Distance from roof edge to outside edge of zone.
[2]Obtained from Figure 19.
[3]$A_z = 2 \tan 2.5° (R_z - R_{z-1}) (R_z + 30)$; for zones S1 through S10.
[4]$A_z = 2 \tan 2.5° (R_z - R_{z-1}) [(R_z + R_{z-1} + 60)/2]$; for zones S11 through S21.

Table 6 Debris Density in Side Recovery Sector for Test 11

Table 7
Full-Scale Safe Debris Distances

Test No.	Measured Safe Debris Distance (ft) to:		Predicted Safe[1] Debris Distance (ft)
	Side	Front	
8	452	500	819
11	549	567	1,131
12	800	458	1,911

[1]From "DISPRE": includes 1.3 safety factor required by DDESB.

Table 7 Full-Scale Safe Debris Distances

Table 8
Measured 1/10-Scale Safe Pressure Distances[1]

Test No.	Measured Safe Pressure Distance (ft) to:		
	Front	Diagonal	Side
8	45.5	44.4	11.6
11	50.8	58.1	21.3
12	91.6	94.4	52.7

[1]Distance from the exterior of the test fixture that the peak pressure decays to 1.2 psi.

Table 8 Measured 1/10-Scale Safe Pressure Distances

Figure 1. Overall site dimensions

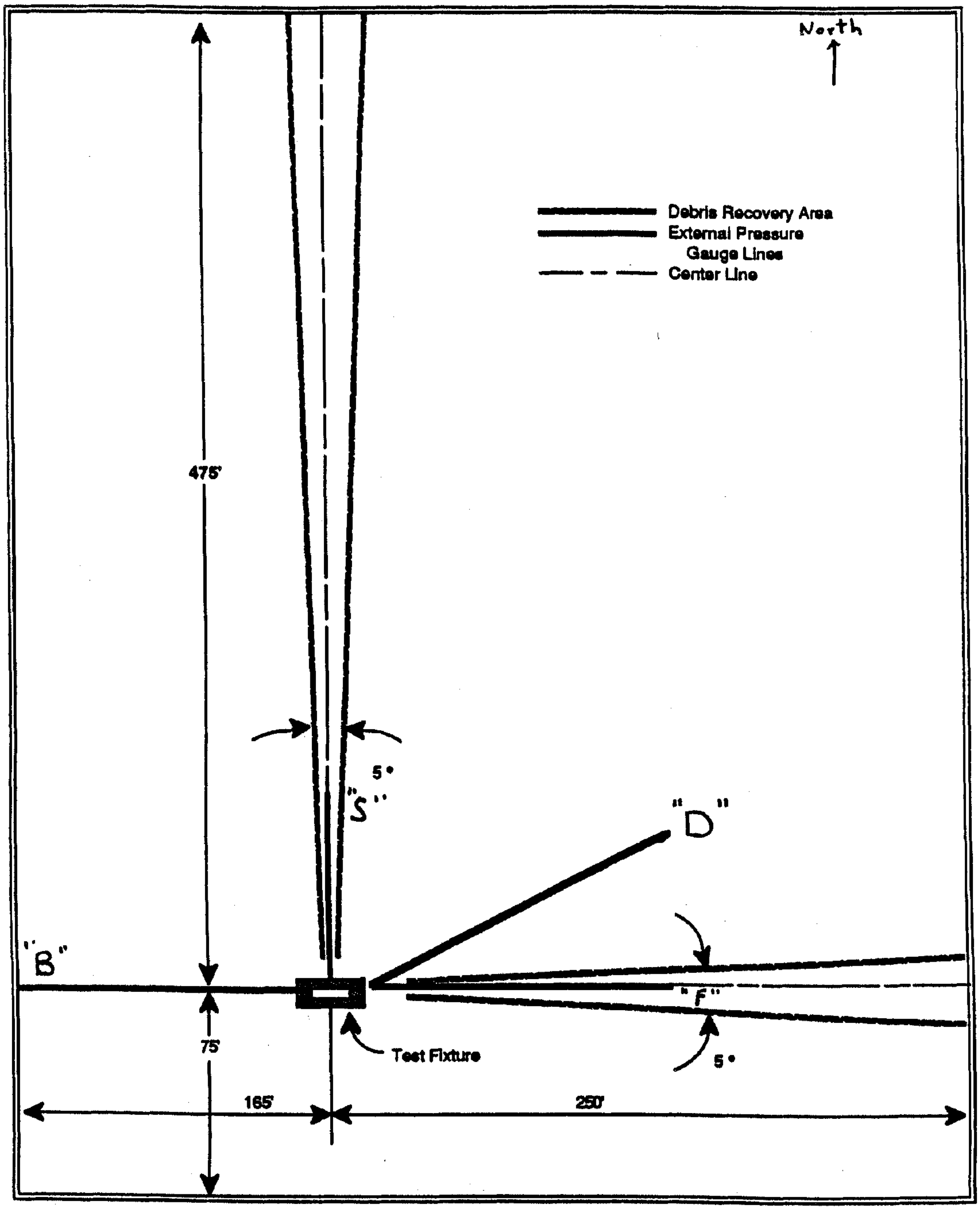


Figure 1. Overall site dimensions.

Figure 2a. Test Fixture: Plan view

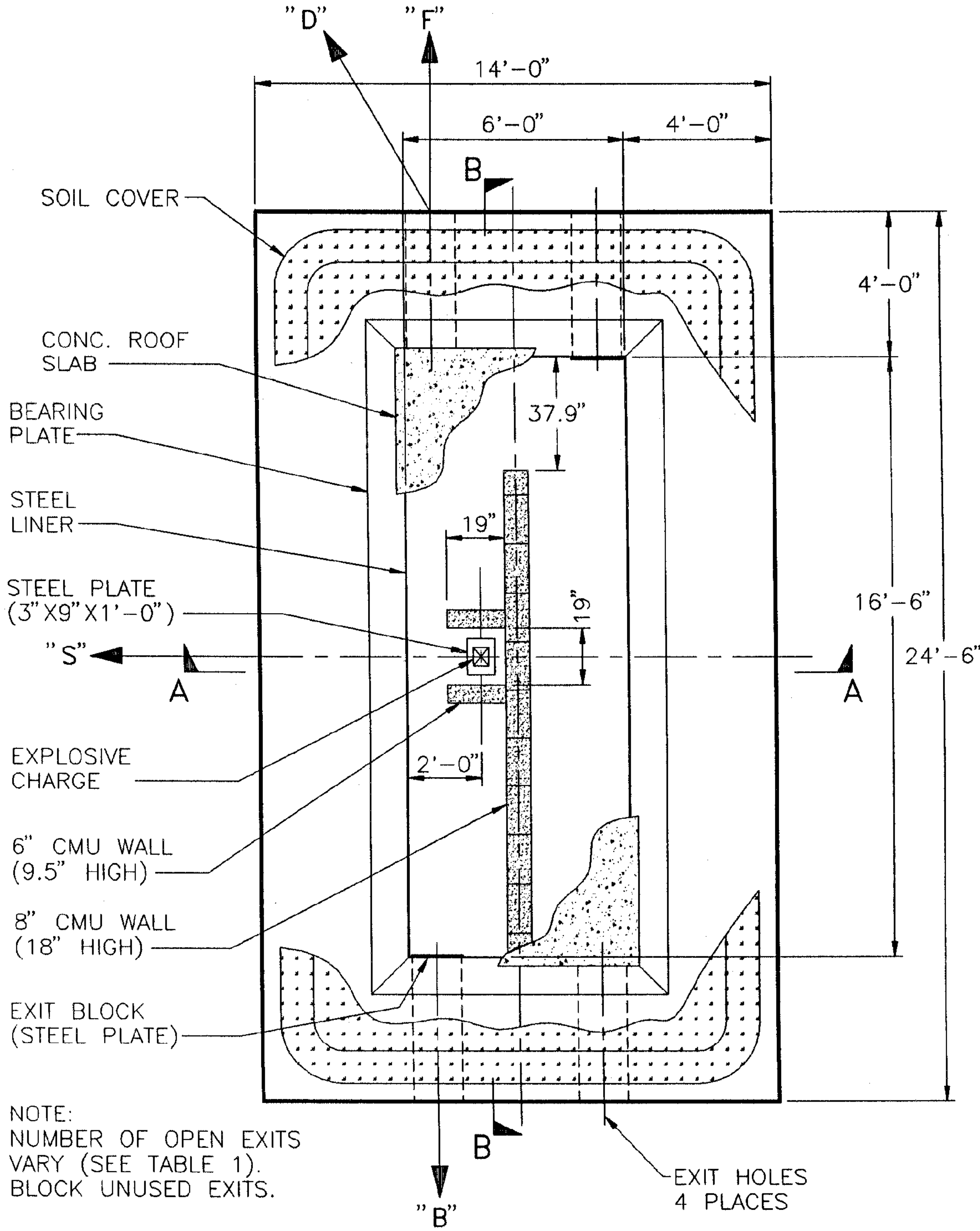


FIGURE 2a. TEST FIXTURE: PLAN VIEW

Figure 2b. Test Fixture: Section A-A

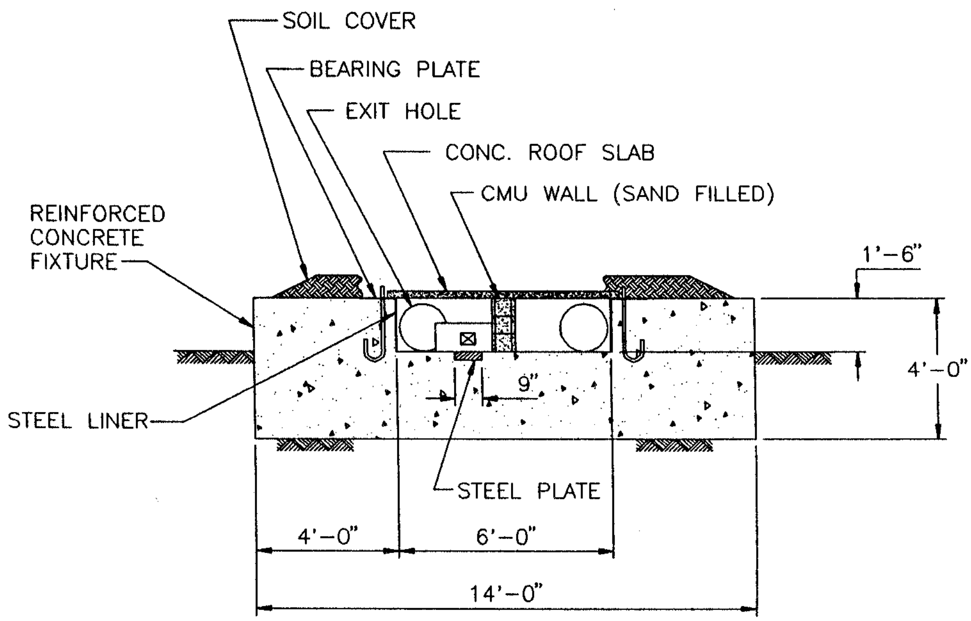


Figure 2c. Test Fixture: Section B-B

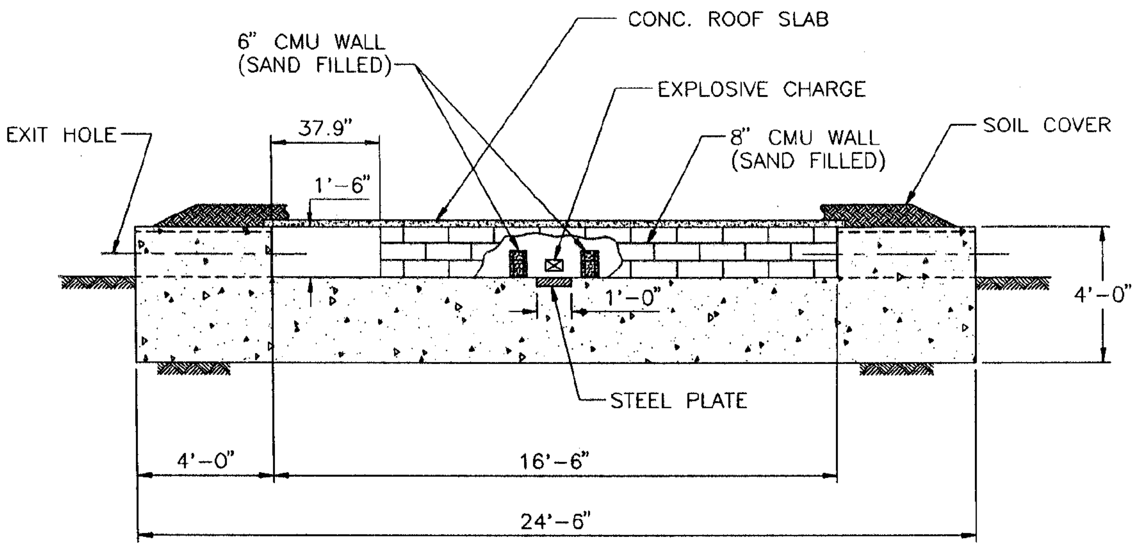
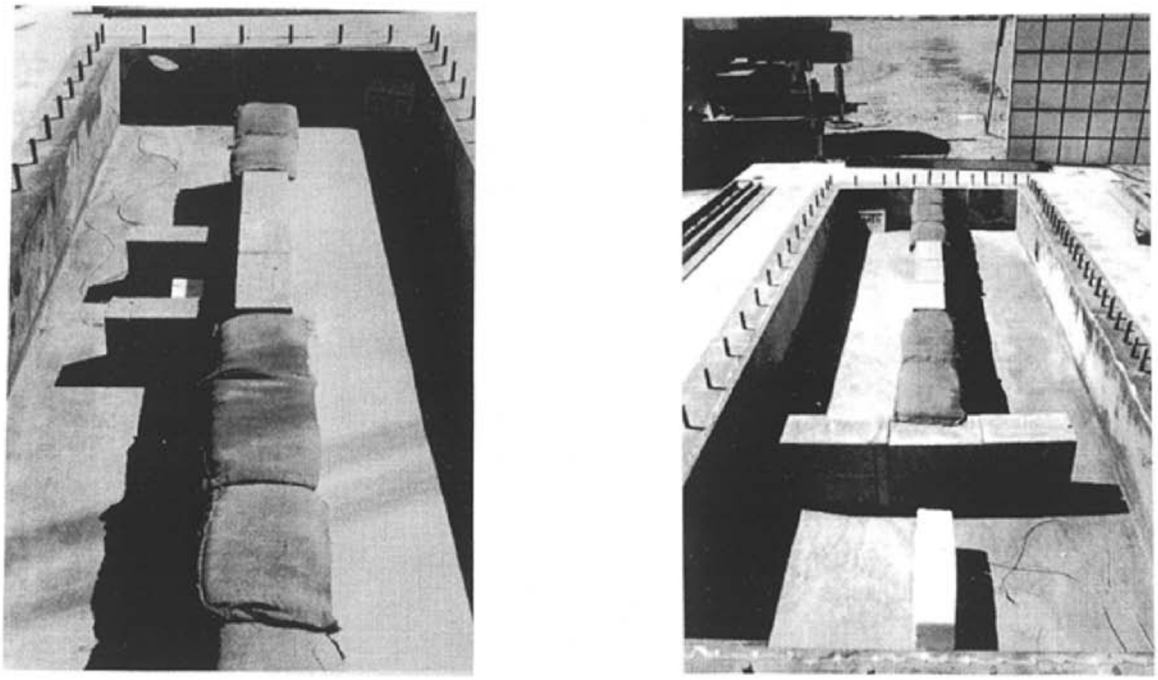


FIGURE 2c. TEST FIXTURE: SECTION B-B

Figure 3. Test Fixture Interior



Test 8 Test 12

Figure 3. Test fixture interior

Figure 4. Roof slab test specimen.

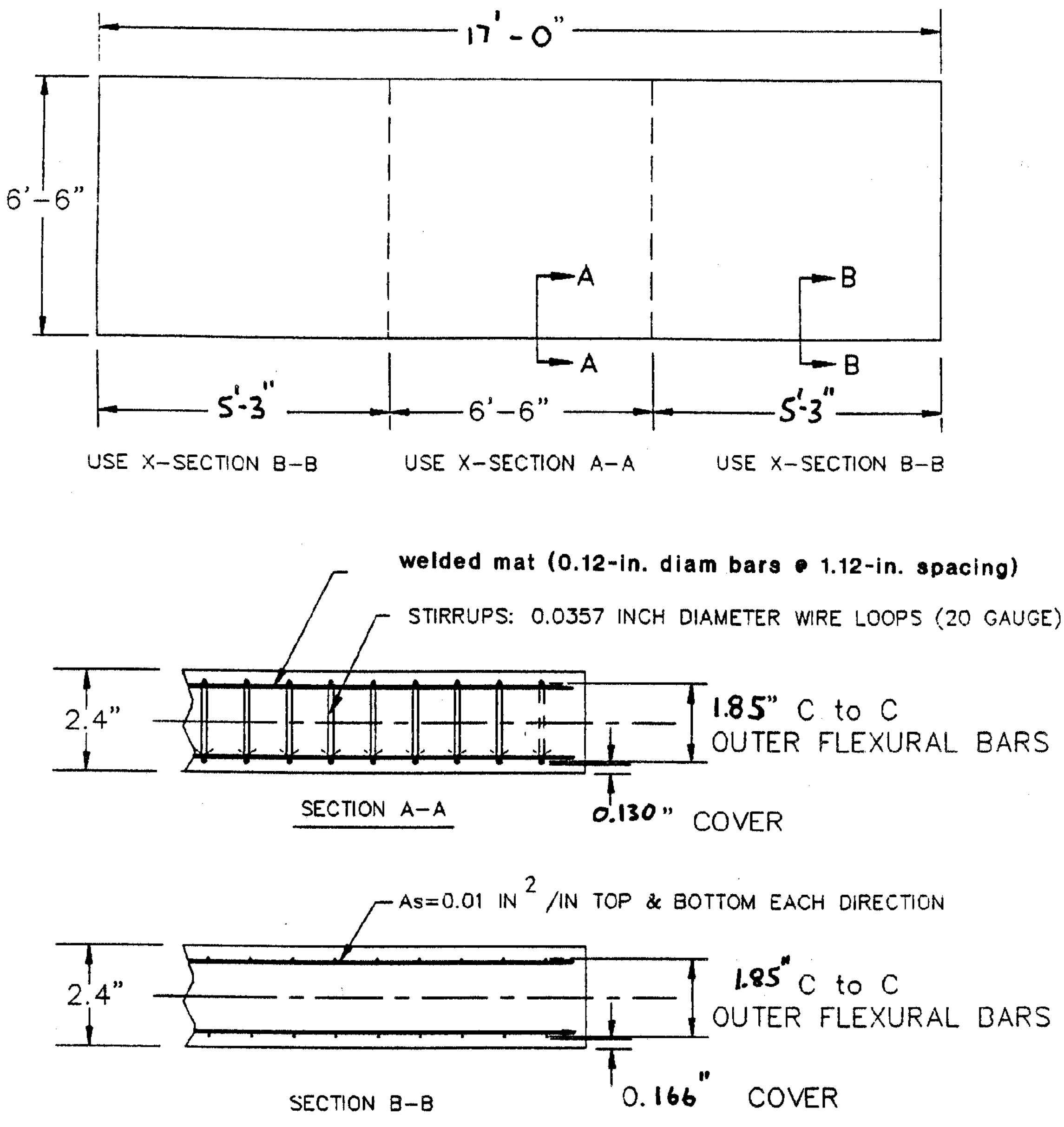


Figure 4. Roof slab test specimen.

Figure 5. Aggregate distribution for 1/10-scale concrete mix.

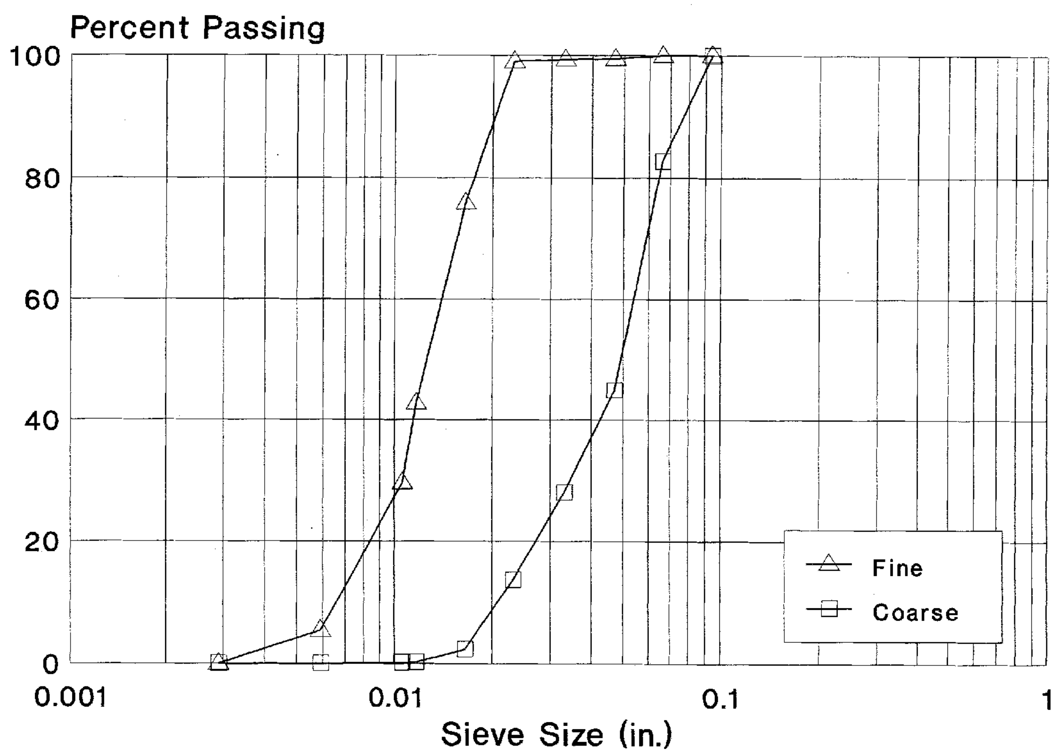


Figure 5. Aggregate distribution for 1/10-scale concrete mix.

Figure 6. Roof slab specimen with soil cover: Test 12.

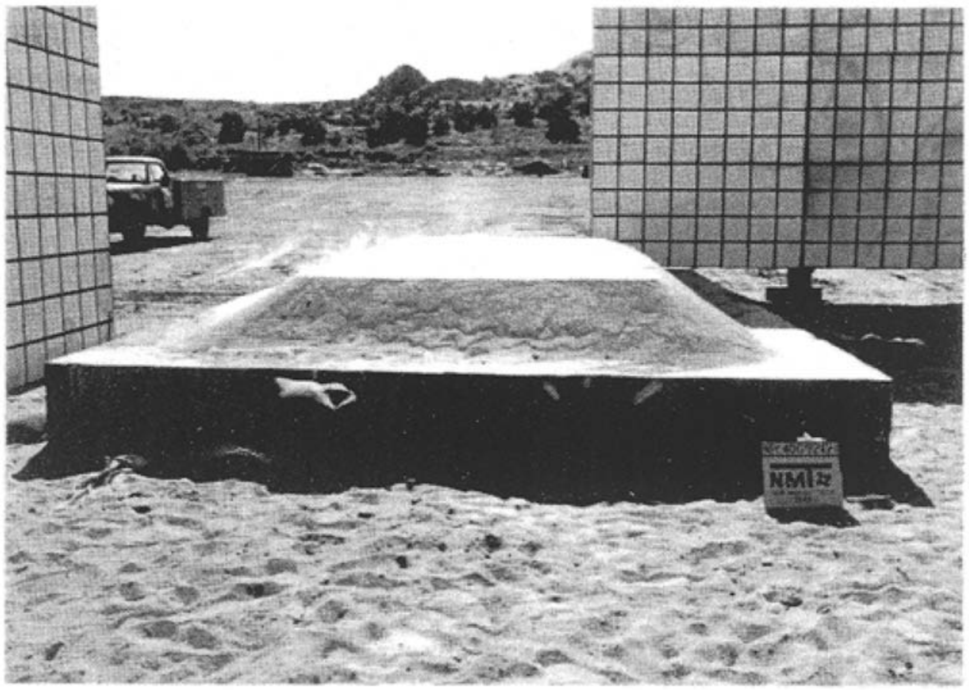


Figure 6. Roof slab specimen with soil cover: Test 12.

Figure 7. Pressure gauge locations.

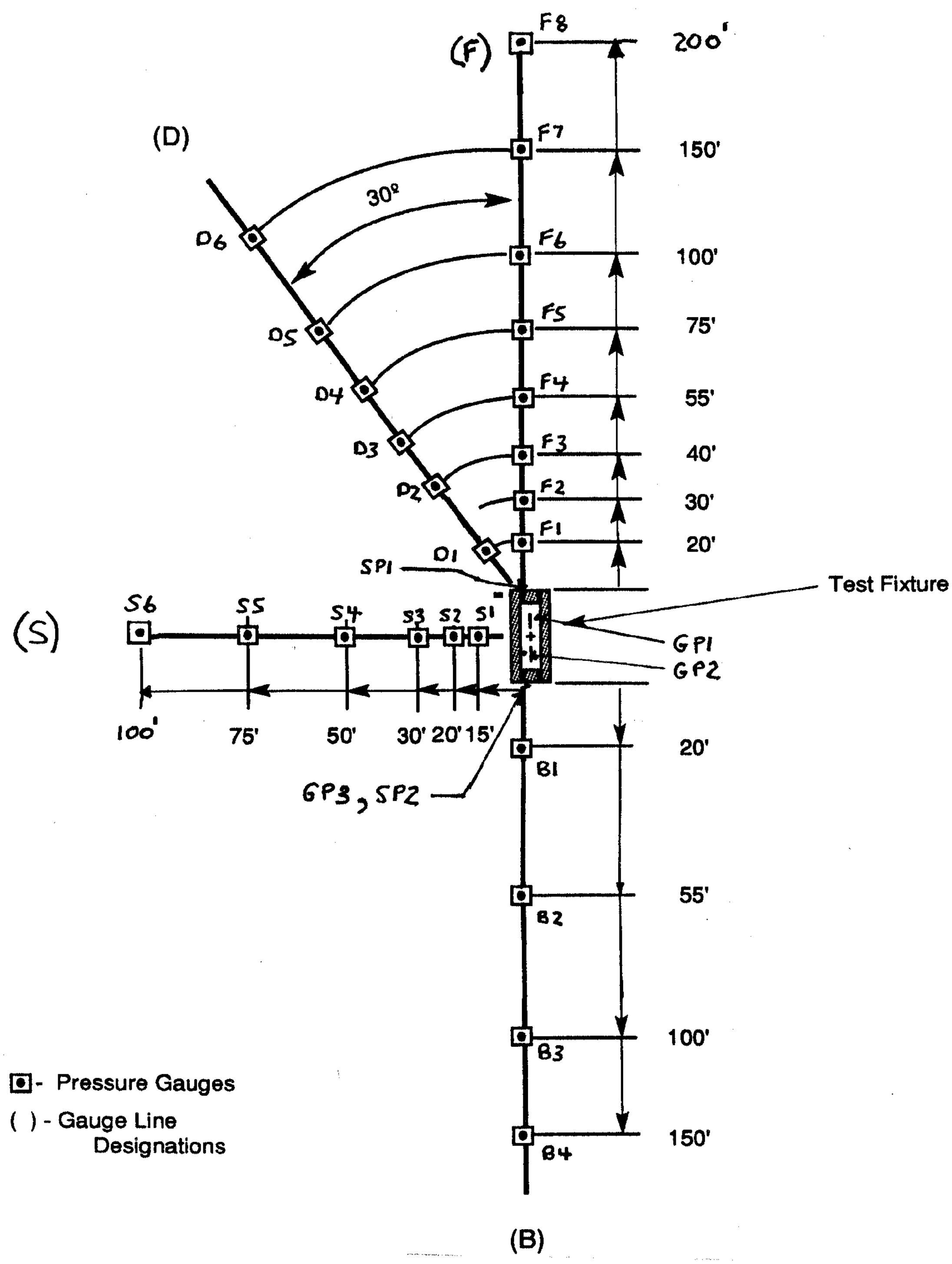


Figure 7. Pressure gauge locations.

Figure 8. Camera locations.

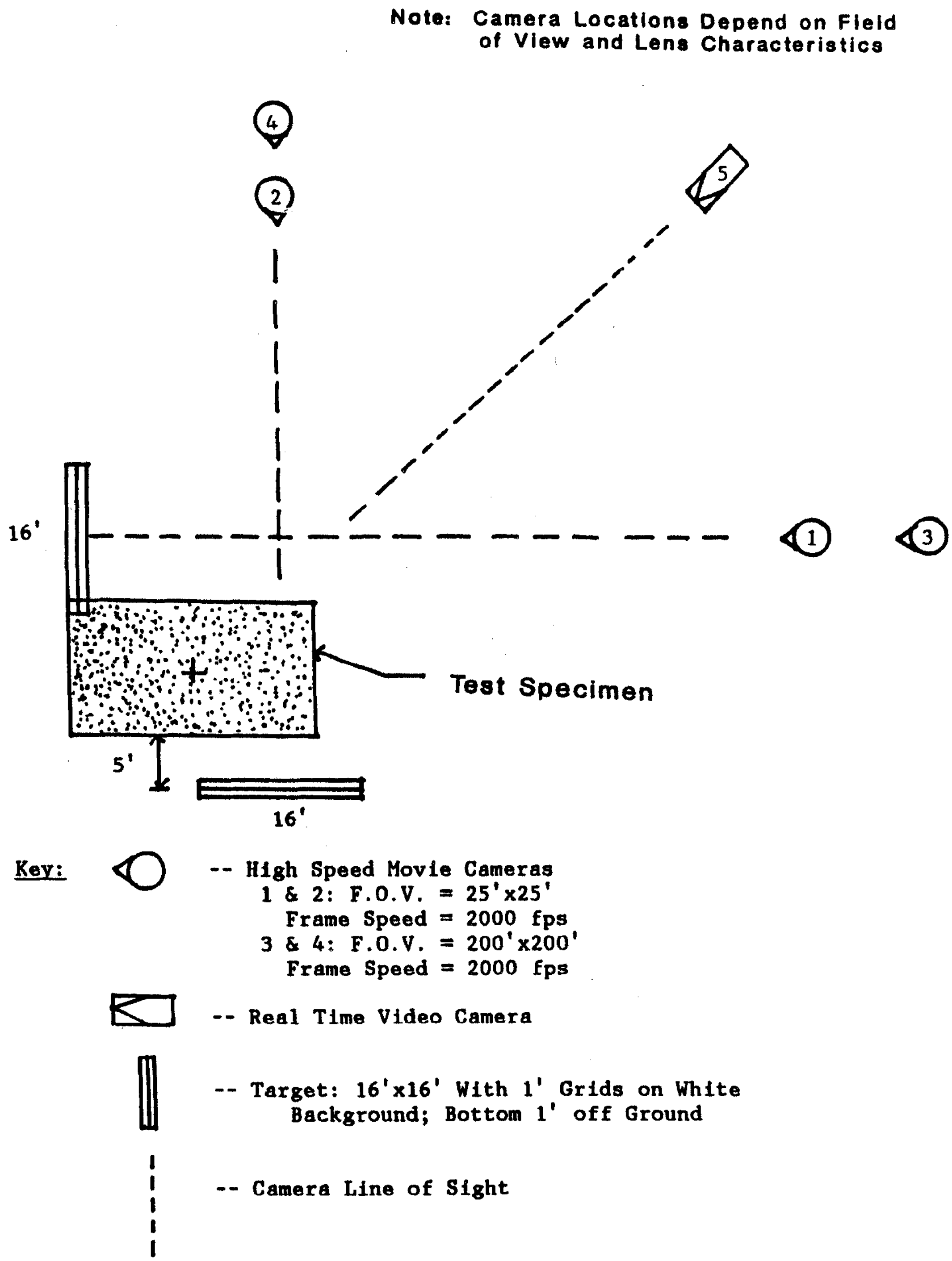


Figure 8. Camera locations.

Figure 9. Debris recovery zones.

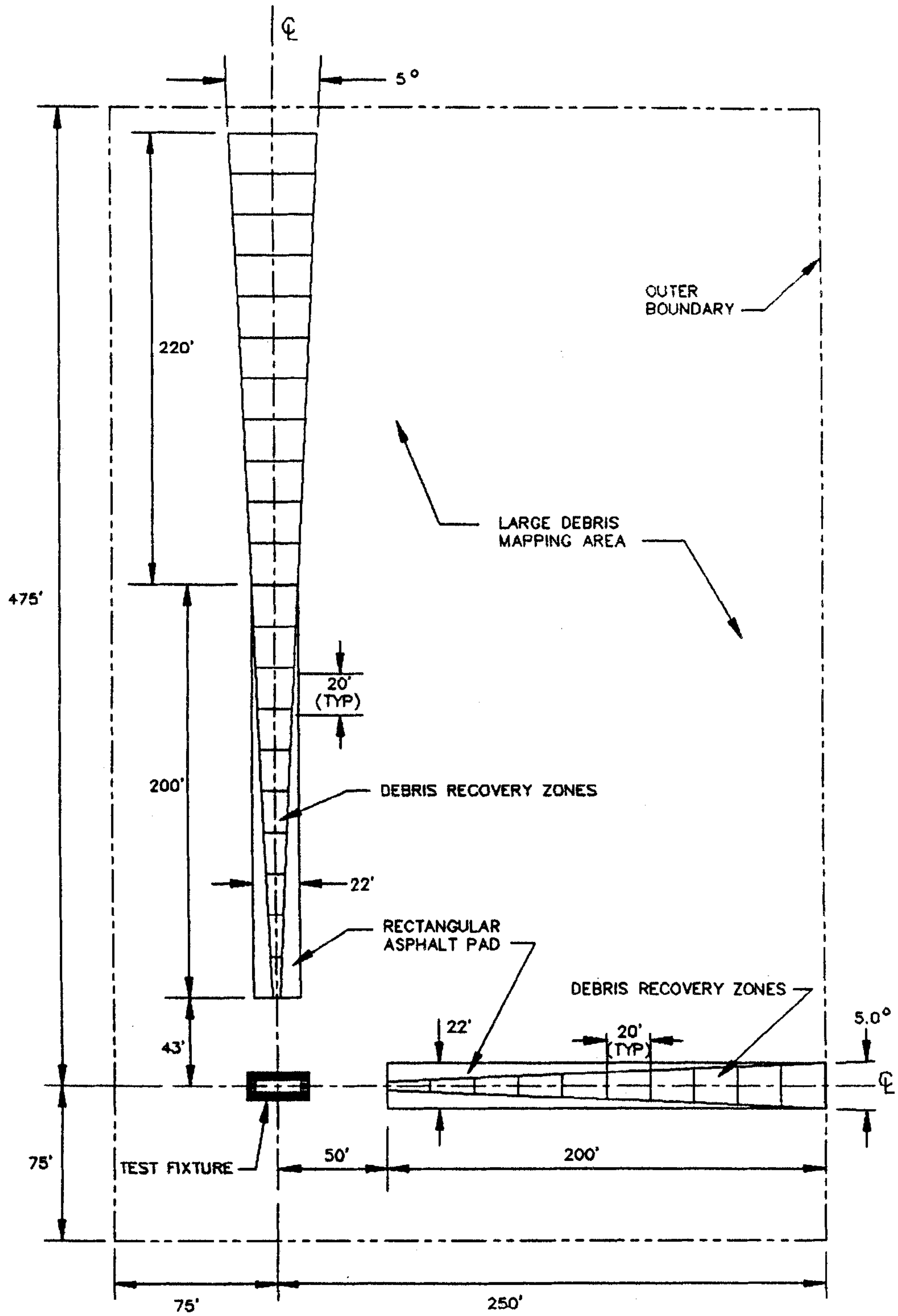


Figure 9. Debris recovery zones.

Figure 10 Typical pressure - time histories.

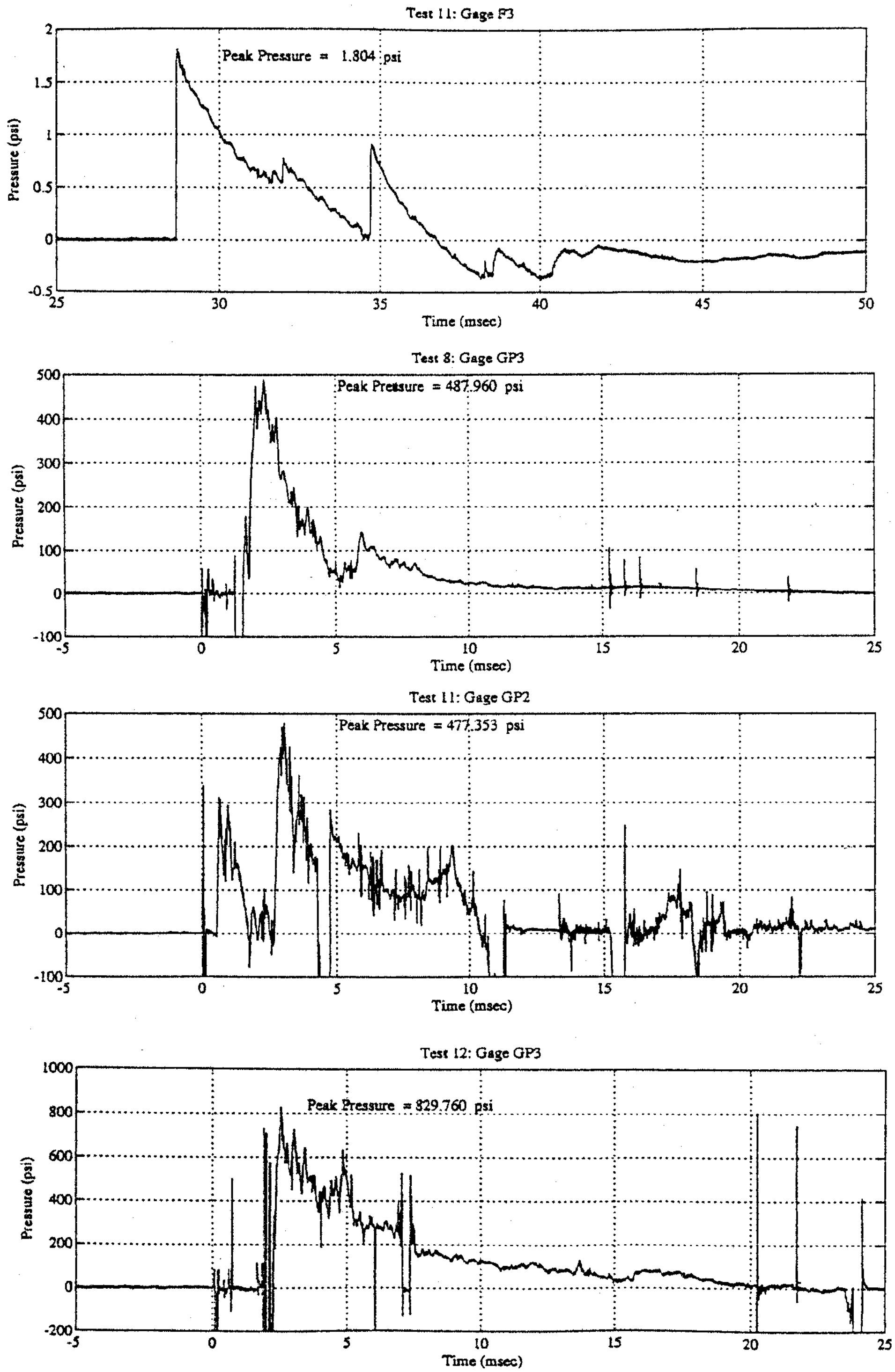


Figure 10. Typical pressure - time histories.

Figure 11. Post - test view of fixture/roof: Test 8.

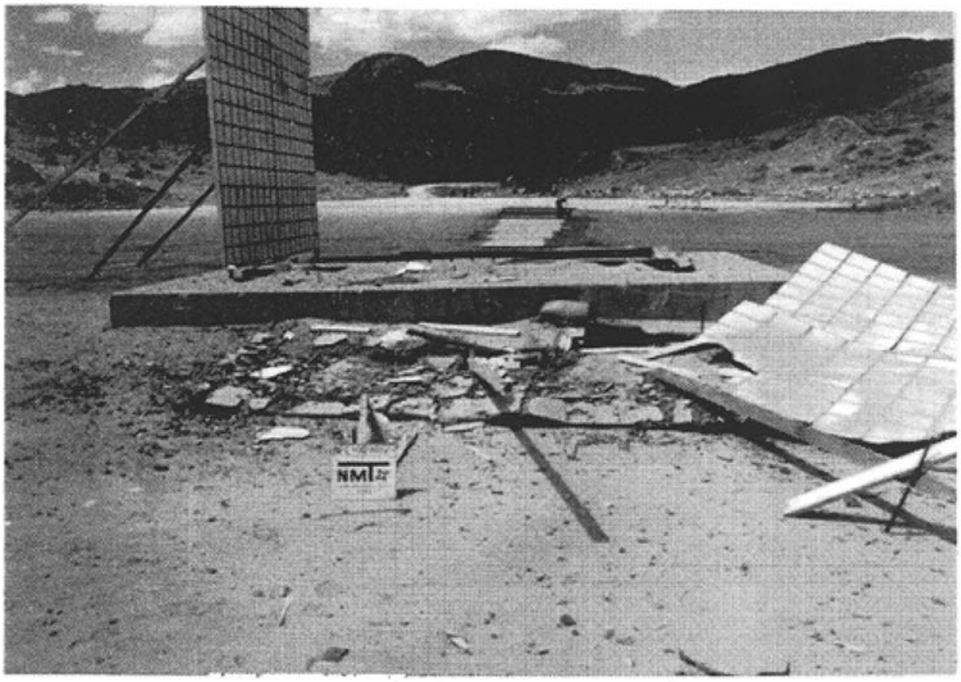


Figure 11. Post - test view of fixture / roof: Test 8.

Figure 12. Post - test view of roof: Test 8.

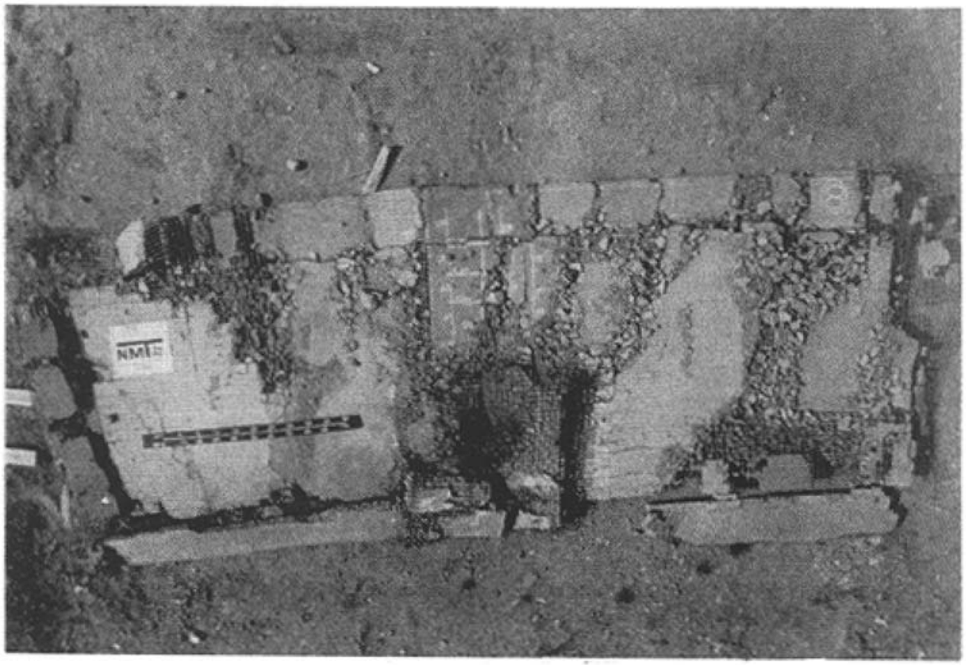


Figure 12. Post - test view of roof: Test 8

Figure 13. Post - test view of roof slab: Test 11.

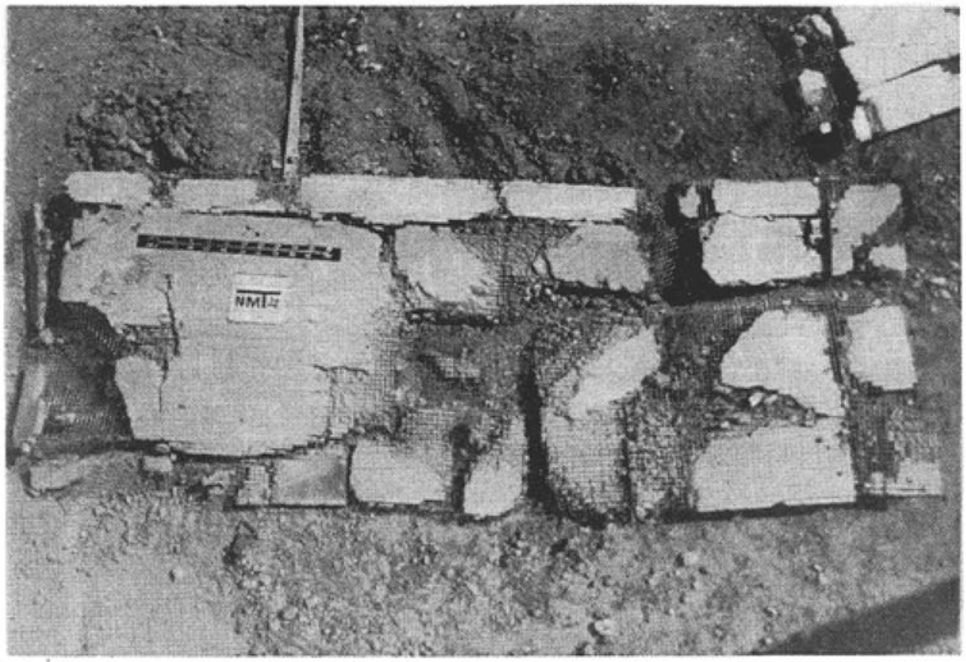


Figure 13. Post - test view of roof slab: Test 11.

Figure 14. Post - test view of roof slab: Test 12.

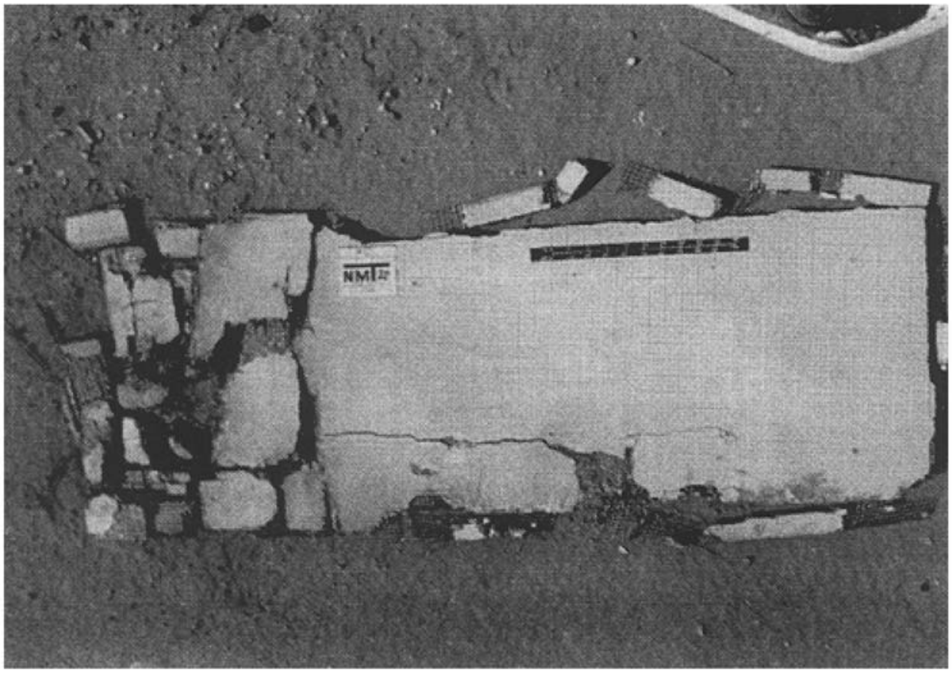


Figure 14. Post - test view of roof slab: Test 12.

Figure 15. Peak pressure vs. range for test 8.

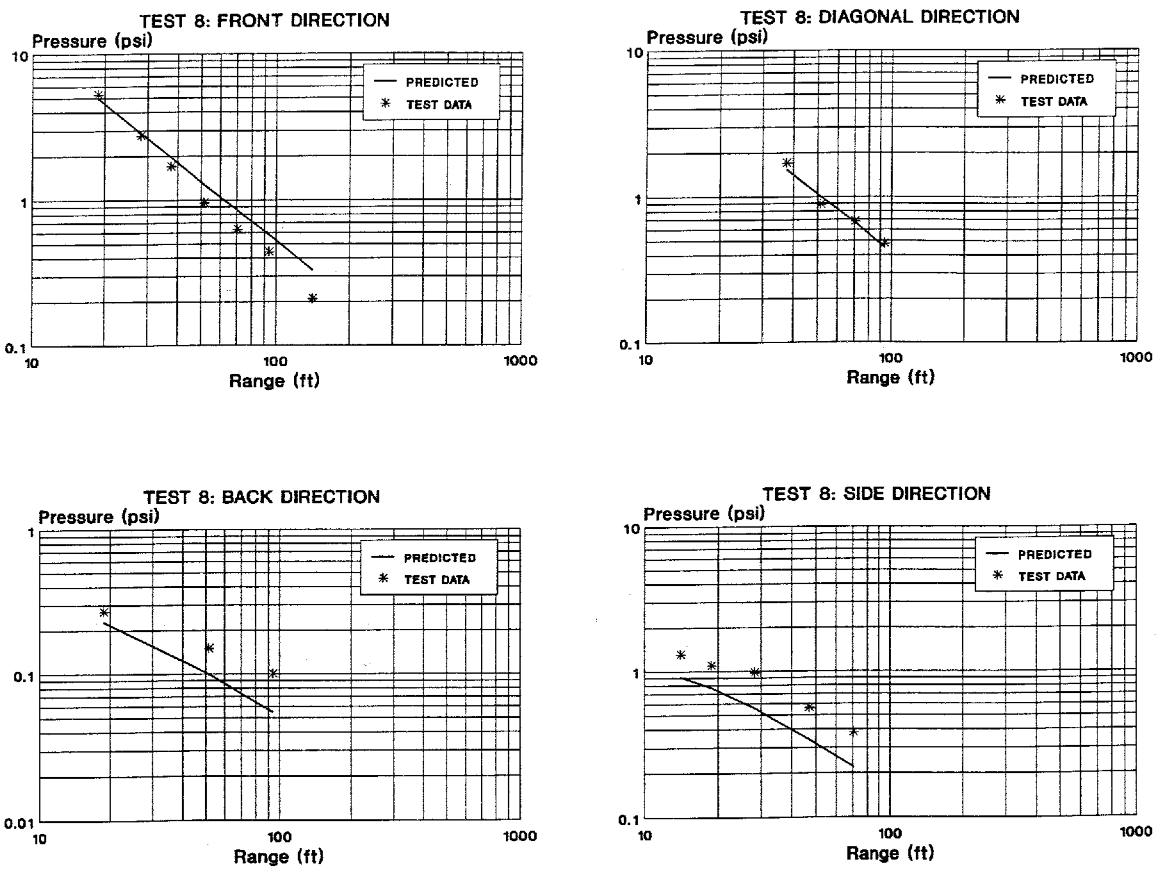


Figure 15. Peak pressure vs. range for Test 8.

Figure 16. Collected debris outside recovery zone: Test 8.

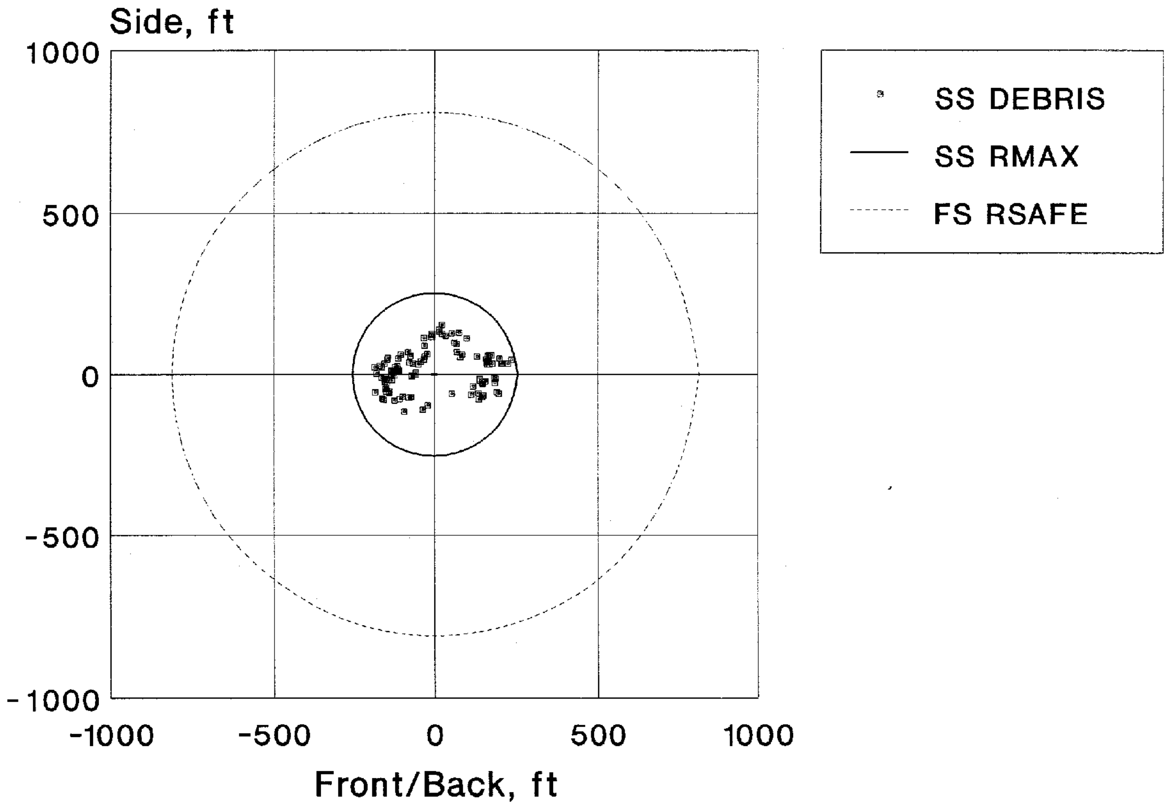


Figure 16. Collected debris outside recovery zones: Test 8.

Figure 17. Collected debris outside recovery zone: Test 11.

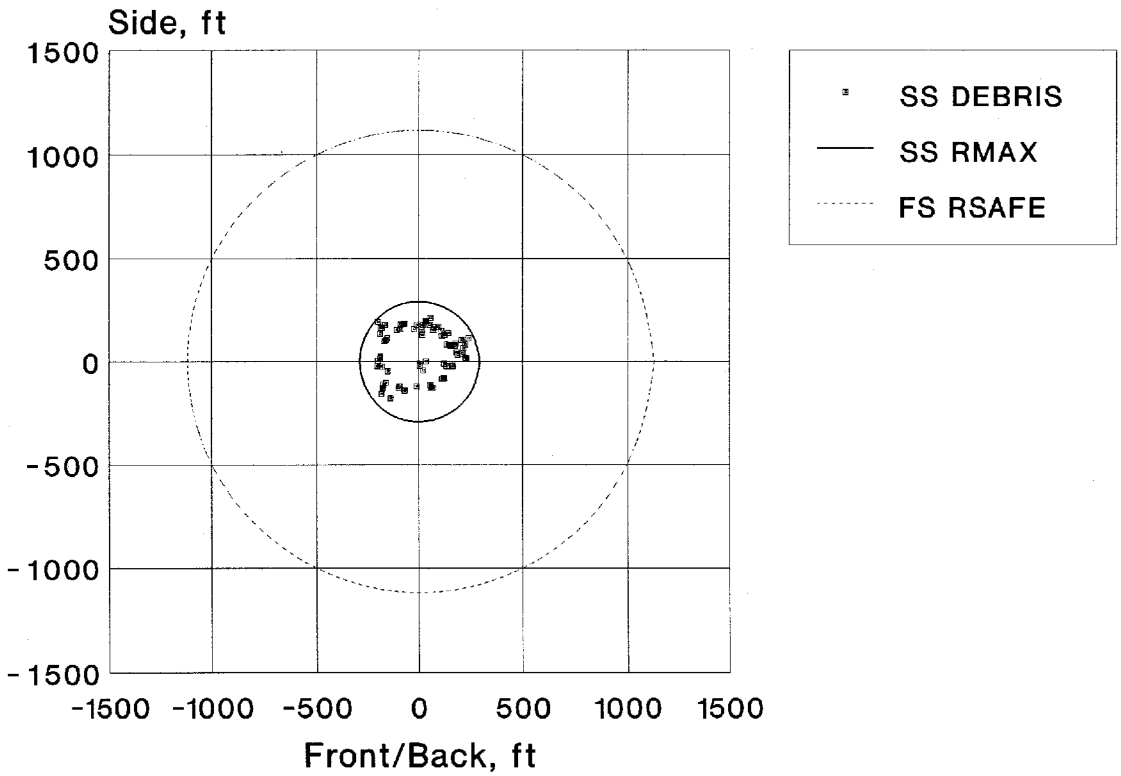


Figure 17. Collected debris outside recovery zones: Test 11.

Figure 18. Collected debris outside recovery zone: Test 12.

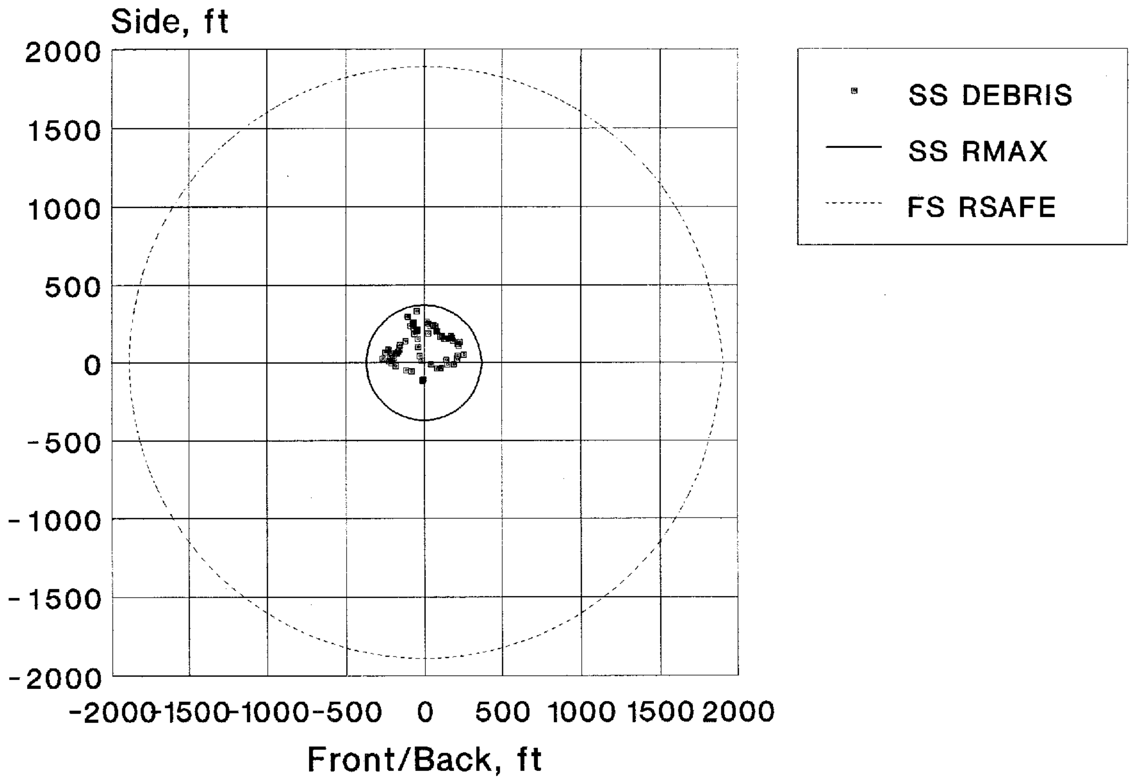


Figure 18. Collected debris outside recovery zones: Test 12.

Figure 19. 1/10-scale debris distance relationship.

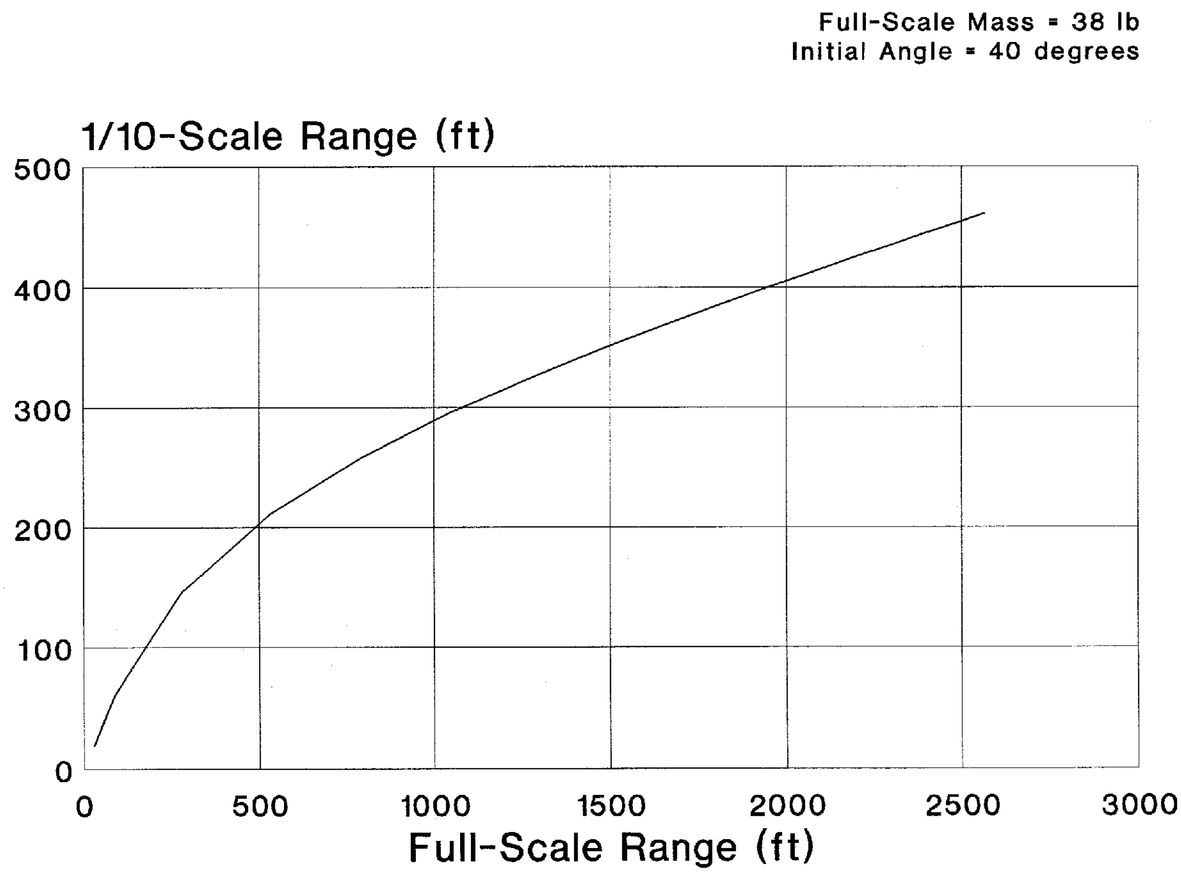


Figure 19. 1/10-scale debris distance relationship.

Figure 20. Debris areal number density distribution.

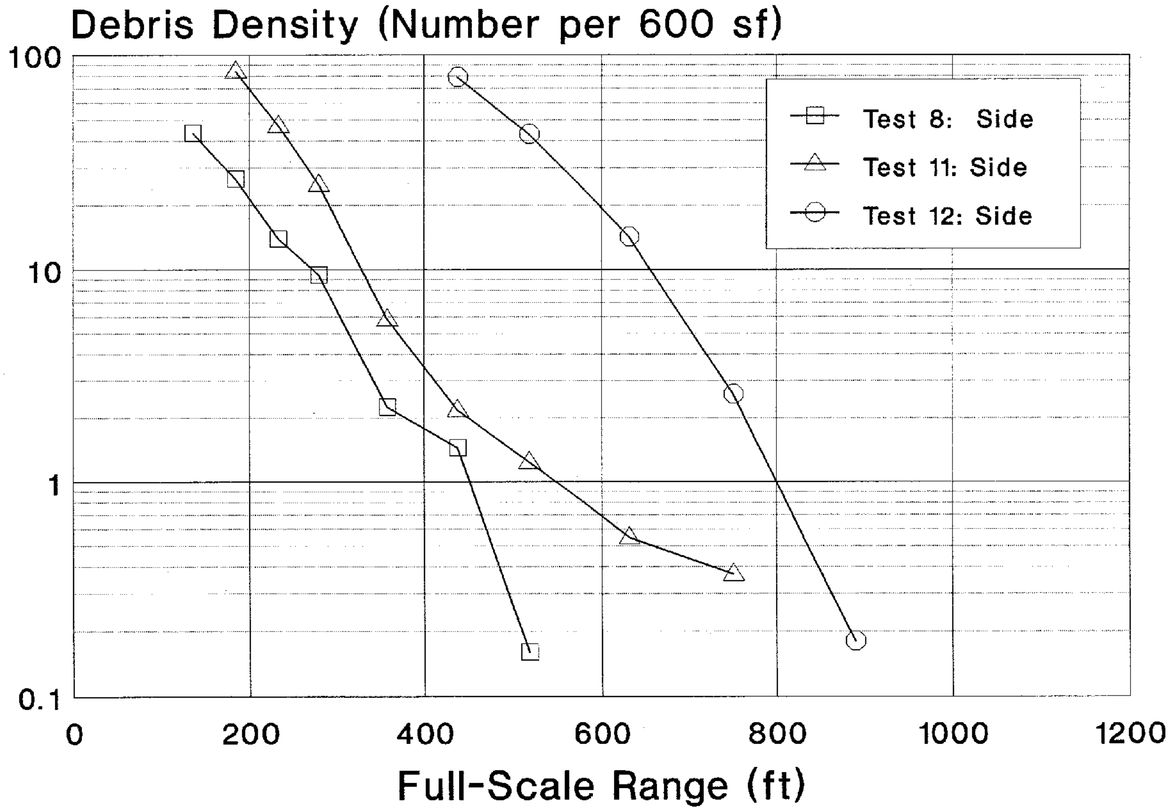


Figure 20. Debris areal number density distribution.

Figure 21. Debris areal number density distribution.

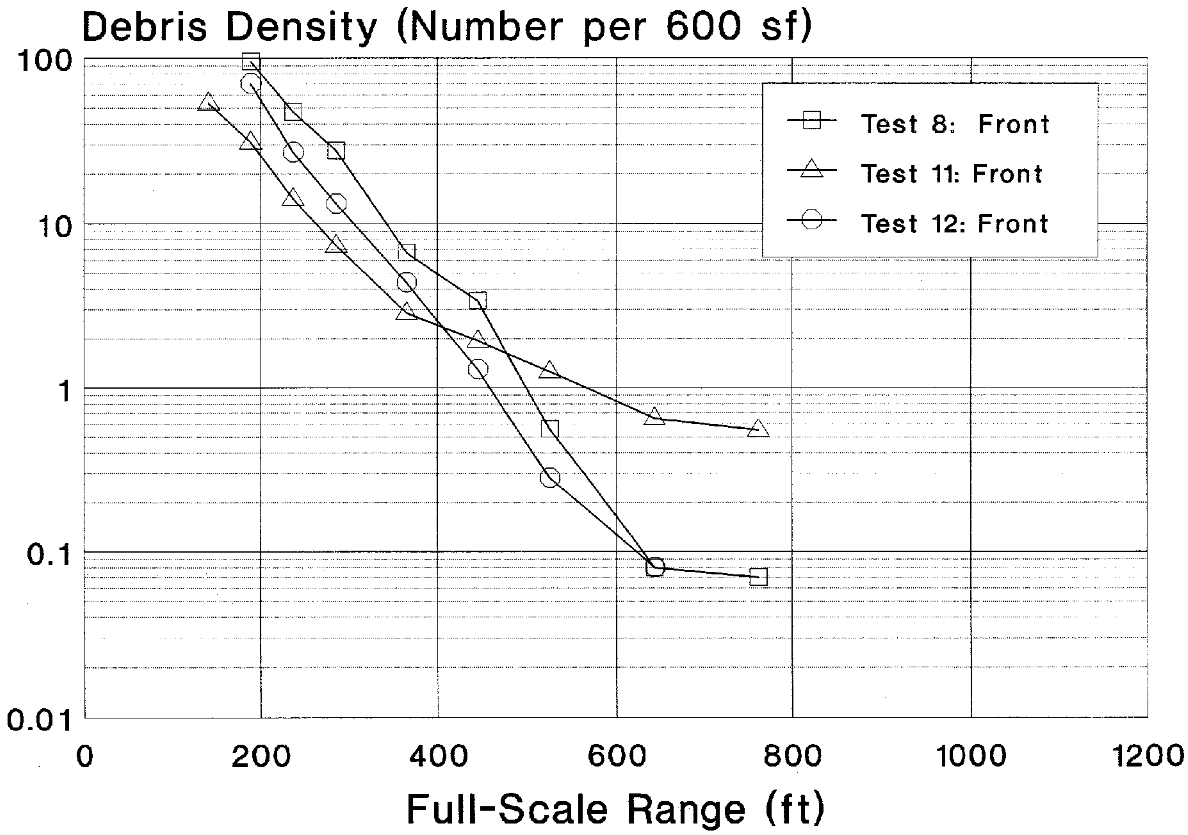


Figure 21. Debris areal number density distribution.